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# Hollow-core photonic crystal fiber Fabry–Perot sensor for magnetic field measurement based on magnetic fluid

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ABSTRACT

Based on the characteristic of magnetic-controlling refractive index, the magnetic fluid filled in hollow-core photonic crystal fiber (HC-PCF) can be used as the sensitive medium in the cavity of a fiber Fabry–Perot (F–P) magnetic field sensor. The structure and the sensor principle are introduced. The theoretical simulations of the mode distribution of the HC-PCF filled with the magnetic fluid and the sensor output spectra are discussed in detail. The sensor multiplexing capability is indicated as well. Magnetic field measurement sensitivity is about 33 pm/Oe based on the proposed sensor.

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## 1. Introduction

Since Lee et al. first reported an optical fiber sensor based on intrinsic Fabry–Perot interferometer (IFPI) in 1988, it has been one of the considerable interests due to its potential applications in optical sensing technologies [1]. In 2004, Shen et al. [2] utilized a focused ultraviolet (UV) laser beam and metallic masks to write local Fresnel reflectors in a $GeO_2$-doped photosensitive fiber that resulted in an IFPI sensor, which has features of low reflectance and low power loss and has the potential to be densely multiplexed. Afterwards, they constructed an IFPI sensor with low reflectance and low power loss by splicing a section of multimode fiber between single mode fibers (SMFs) [3] in 2005. In 2007, Rao et al. [4] first proposed a novel IFPI sensor by splicing a section of photonic crystal fiber between the signal-mode fibers, and used it to form a refractive index sensor [5]. In 2010, Zhu et al. reported a novel Fabry–Perot optical fiber tip sensor for high temperature measurement. The reflex sensor consists of a short section of a special all-silica photonic crystal fiber spliced at one end to a silica single-mode fiber [6].

The cavity of the fiber IFPI sensor is composed of different kinds of fibers, so the transmission loss in the cavity is low and the length of the sensing fiber could be long, resulting in a strong multiplexing capability. Besides, for temperature sensing, fiber IFPI sensor could also be used as a strain sensor, refractive index sensor, and so on. Temperature cross-sensitivity, however, is a key problem for this kind of sensors.

In 1991, Murphy et al. [7] developed the earliest fiber Extrinsic Fabry–Perot Interferometer sensor by placing and fixing two fibers in a collimating capillary tube with a distance. This kind of fiber sensor has a much better adaptability by selecting different kinds of incident fibers and reflected fibers, using different material of the capillary tube, or by changing the structural parameters of the fiber cavity. Unlike the IFPI sensors, the cavity of the fiber EFPI sensor is not made of fibers, so its transmission loss is larger than that of the IFPI sensors.

In this paper, a hollow-core photonic crystal fiber (HC-PCF) is used to constitute the cavity of the fiber F–P sensor, which has the merits of being insensitive to temperature and low transmission loss. Since the refractive index of magnetic fluid is sensitive to the magnetic field, the core of the hollow-core PCF filled with the magnetic fluid could be used as a magnetic sensor based on the previous works of infiltrated art [8,9]. When the external magnetic field strength is not zero, the optical path difference could vary with the change of the refractive of the magnetic fluid, and then the spectrum of the EFPI would shift.

Therefore the magnetic fluid filled in the hollow-core of the PCF could be used as a magnetic field sensor.

## 2. Sensor design and fabrication

The magnetic fluid filled in HC-PCF based on fiber F-P sensor includes a section of HC-PCF and a standard single-mode fiber. Only the central core is filled with magnetic fluid. The paraffin is used to block the other holes, not the hollow core, and then utilize

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the capillarity to fill the hollow core with the magnetic fluids. The other end of the HC-PCF splices with the end of the standard single-mode fiber stuck with a partially reflecting and partially transmitting $Ti_2O_3$ film. And then let the magnetic fluid flow to the splicing joint, and cut off the HC-PCF in a proper length and a fully reflecting mirror is stuck on the end of the HC-PCF with magnetic fluid. The F–P sensor is set as a reflex sensor structure design.

As in the F–P sensor, the interference signal contrast is the most important factor in practical applications. If the splicing quality is good enough, based on the theory of Fresnel reflection, the reflectivity at the point of splicing mainly depends on the refractive index difference of the SMF core and the magnetic fluid. The refractive index difference of these two materials is very small and the reflectivity at the splicing point is very small, which results in no interference. So a partially reflecting and partially transmitting $Ti_2O_3$ film must be used here to increase the reflectivity.

The magnetic fluid is filled in the hollow core of the HC-PCF based on the capillary phenomena. The sensor structure is shown in Fig. 1.

## 3. Magnetic field measurement principle

The schematic diagram of the magnetic field measurement system based on the proposed magnetic fluid filled in HC-PCF F–P sensor is shown in Fig. 2. The light from the Broadband light source (BBS) is split into two parts by a $2\times2$ optical coupler: one is received by the Index Matching Gel (IMG) and the other goes into the F–P sensor. The reflected light signal from the sensor is coupled into an optical spectrum analyzer (OSA). The computer is used to process the output signal and to control the driving current for the electromagnetic coil, which can produce a variable magnetic field.

The fiber F–P sensor is based on the principle of an F–P interferometer. In this paper, the sensor is designed as a reflex type structure, so the output reflected light intensity $I^{(r)}$ from the sensor could be described as:

$$I^{(r)}=\frac{R_1+q^2R_2-2q\sqrt{R_1R_2}\cos\delta}{1+q^2R_1R_2-2q\sqrt{R_1R_2}\cos\delta}I^{(i)} \tag{1}$$

where, $R_1$ is the reflectivity at the point of splicing the HC-PCF and SMF, $R_2$ is the reflectivity of the fully reflecting mirror, $q$ is the loss coefficient at the point of splicing the HC-PCF and SMF, and $\delta$ is the phase difference of the light in the cavity, which could be given by:

$$\delta=\frac{4\pi nL}{\lambda} \tag{2}$$

where, $n$ is the refractive index of the medium in the cavity (here is that of the magnetic fluid), and $\lambda$ is the light wavelength.

Based on the research result of Chen et al. [10] under the temperature $T$, the relationship between the refractive index of the magnetic fluid and the applied magnetic field is:

$$n=(n_s-n_0)\left[\coth\left(\alpha\frac{H-H_c}{T}\right)-\frac{T}{\alpha(H-H_c)}\right]+n_0,\quad H>H_c \tag{3}$$

where, $H_c$ is the critical value of the magnetic field, $n_0$ is the refractive index of the magnetic fluid under the critical magnetic field, $n_s$ is the saturation value of the refractive index of magnetic fluid, and $\alpha$ is a fitting coefficient. It is regarded that for a certain kind of magnetic fluid film, $n_s$, $n_0$, $\alpha$, $H_c$ are constants. So at a certain value $T$, there will be a certain $n$ versus a certain $H$. The measurement of the parameters uses the method of Ref. [10]. The magnetic fluid is injected into a glass cell with a certain depth, and then it was covered with a triangle prism made of the materials, which are transparent to light with a wavelength around 1.5 μm. The prism is in direct contact with the MF. The critical angle of the total reflection at the interface between the prism and the MF is then measured and the refractive index is calculated. There is a uniform magnetic field $H$ perpendicularly to the film plane provided by electromagnetic coil.

From the above theory and equations, by controlling the driving current into the electromagnetic coil, magnetic field around the sensor probe could be changed, which results in the variation of the refractive index of the magnetic fluid. Since the quantity of heat is increasing with the increasing of current of the electromagnetic coil, then the electromagnetic coil is designed to work in a low current state, and then the heating phenomenon could be ignored. As the sensing medium in the interferometer cavity, the variation of the refractive index of the magnetic fluid will cause the output spectrum change of the fiber

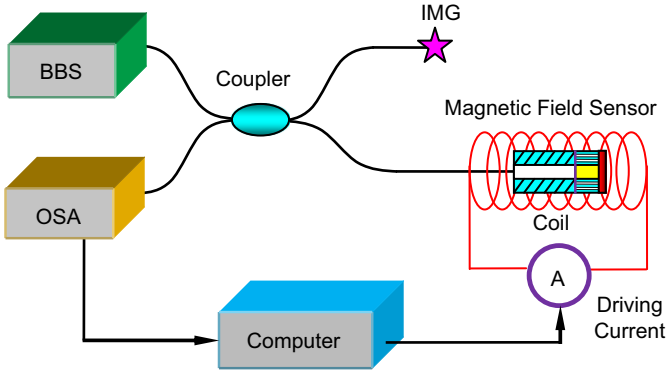


**Fig. 2.** Structure diagram of the sensor experimental system.

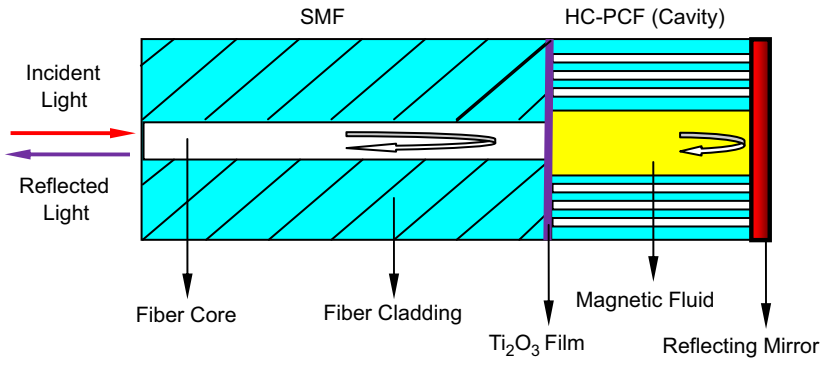


**Fig. 1.** Structure diagram of magnetic filled hollow-core photonic crystal fiber F–P sensor.

F–P sensor, so the magnetic field could be measured by recording the output of the proposed fiber F–P sensor.

## 4. Results and discussion

Water-based $CdFe_2O_4$ is used as the magnetic fluid, the concentration of which is 0.85 emu/g, and the filling length (cavity length of the F–P sensor) is about 200 μm. The outer diameter of the hollow-core PCF is 125 μm, the inner diameter of the hollow core is 40 μm, the pitch of the PCF is 3.8 μm, and the diameter of the hole in the cladding is 3.74 μm. The radius of the electromagnetic coil is 5 mm, the length is 60 mm, and the turn number is 500. And the operated temperature is 24.3 °C. The output spectra of the fiber F–P sensor with different refractive indexes of the magnetic fluid are shown in Fig. 3.

The triangle markings show the shifts of one of the resonance peaks in the interferometer spectra with different refractive indexes of the magnetic fluid, which indicates that the output spectra will shift to a longer wavelength direction with the increase of the refractive index of the magnetic fluid. Because of the increasing of the refractive index of the magnetic fluid, the optical path difference of a certain wavelength light will be longer. For maintaining the value of optical path difference under the increasing of the refractive index of magnetic fluid, the wavelength of the light should increase according to the Eqs. 1 and 2. So the output spectra will change to a longer wavelength side. So by tracing the shifts of one of the resonance peaks, the relationship of magnetic fluid refractive index versus one resonance peak could be obtained as shown in Fig. 4.

Based on the characteristic of magnetic-controlled refractive index, the relationship of magnetic field intensity versus one resonance peak is shown in Fig. 5, from which the magnetic field intensity measurement sensitivity about 33 pm/Oe could be obtained. And if the wavelength measurement resolution of the OSA is 1 pm, the magnetic field intensity measurement resolution can reach 0.03 Oe, and the measurement range is from 50 Oe to 150 Oe at temperature of 24.3 °C.

With the development of the magnetic fluid technology, some new magnetic fluid with larger transmission factor could be produced. So such fiber F–P magnetic field sensors with different cavity lengths could be developed and their output spectra are shown in Fig. 6 with the cavity length of 70 μm, 100 μm, 300 μm, and 500 μm. From Fig. 6, we can see that the output spectra of fiber F–P sensors with different cavity length have different frequencies. The signals with different frequencies could be easily measured using the method of Fast Fourier Transform. So multiplexing of this kind of sensor is possible.

In addition to the above-mentioned multiplexing method, using different magnetic fluid with different refractive index change will also make the multiplexing available.

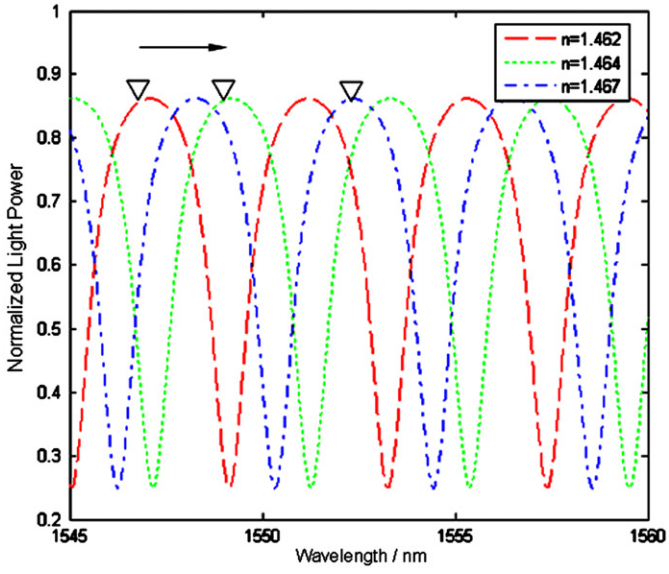


**Fig. 3.** Sensor output optical spectrum under different MF refractive indexes.

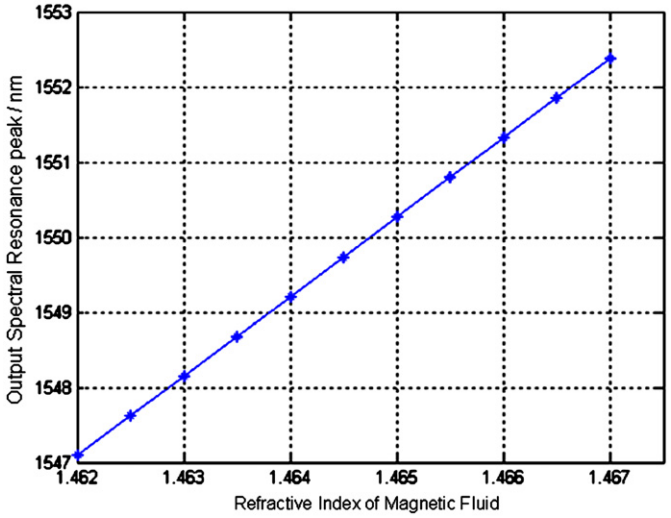


**Fig. 4.** Relationship of magnetic fluid refractive index and sensor output spectral resonance peak.

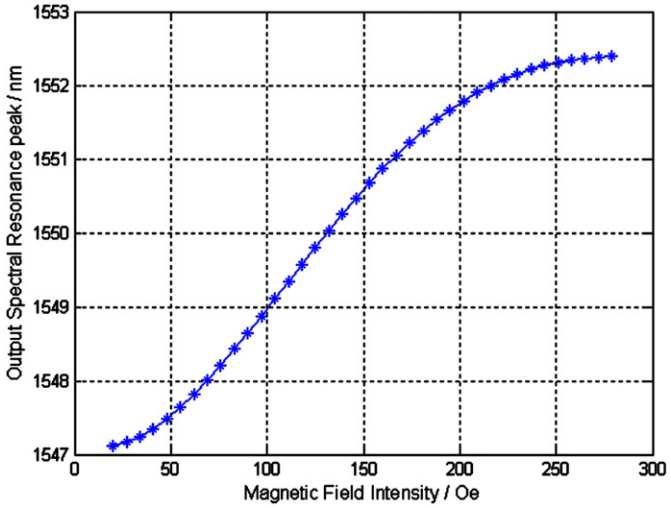


**Fig. 5.** Relationship of magnetic field intensity and sensor output spectral resonance peak.

## 5. Conclusion

A novel fiber F–P sensor used for magnetic field measurement is proposed in this paper. The sensor characteristics have been simulated. From our experimental results, the phase difference delta is matched under the tolerance of the error. The merits of this kind of sensor include its simple structure, small volume, and convenience for multiplexing. Magnetic field measurement resolution could reach 0.03 Oe at 24.3 °C, which is about 0.01% in the full measurement range.

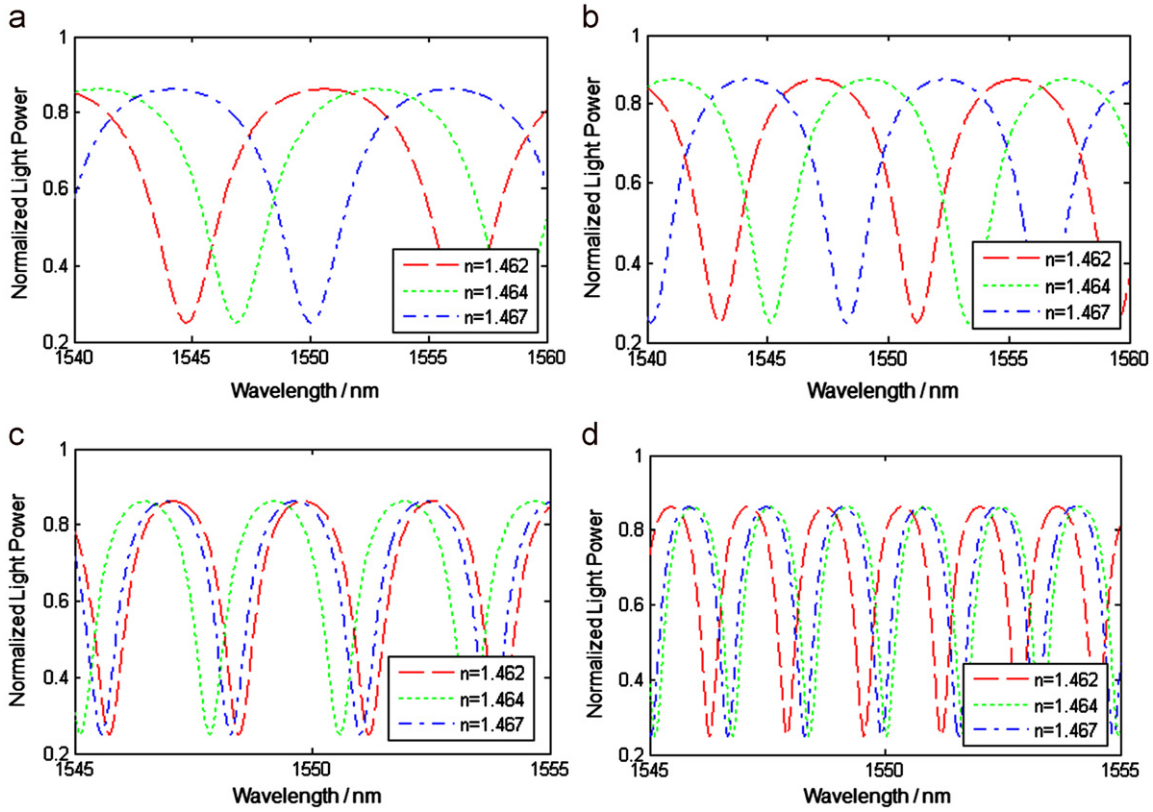


**Fig. 6.** Sensor output optical spectra in different F–P cavity. (a) $L$=70 μm, (b) $L$=100 μm, (c) $L$=300 μm and (d) $L$=500 μm.

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